PSR NOTE 983

EXTREMELY LOW FREQUENCY (ELF) RADAR (ACTIVE MAGNETIC ANOMALY DETECTION)

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October 1989

Contract No. N62269-89C-0561

Sponsored by
Naval Air Development Center
Code 501
Warminster, PA 18974

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
xx-10-1989

2. REPORT TYPE
Phase Technical

3. DATES COVERED *(From - To)*
To October 1989

4. TITLE AND SUBTITLE
Extremely Low Frequency (ELF) Radar
(Active Magnetic Anomaly Detection)

5a. CONTRACT NUMBER
N62269-89-C-0561

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Moser, Paul M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Pacific-Sierra Research Corporation
Warminster, PA 18974

8. PERFORMING ORGANIZATION REPORT NUMBER
PSR Note 983

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Air Development Center, Code 501
Warminster, PA 18974

10. SPONSOR/MONITOR'S ACRONYM(S)
NAVAIRDEVCEN

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report explores the possibility that an extremely low frequency (ELF) radar could be built to detect submerged submarines at militarily significant distances. Two ELF sources are considered: (1) a large-area coil of copper wire wrapped around an aircraft (wingtip to tail to wingtip to nose to wingtip) through which a large alternating current would be passed and (2) a rotating superconducting electromagnet, which might be mounted on a ship or an aircraft. Factors influencing the choice of frequency, propagation of ELF waves in sea water, conflicting desiderata, calculated signal strengths, and receiver sensitivity requirements are considered. It is concluded that these approaches are not feasible.

15. SUBJECT TERMS
Submarine, Detection, ASW, ELF Radar, Aircraft, Superconducting Electromagnet, Air-Core Electromagnet, Sea Water, ELF Propagation, Signal Strength, Receiver Sensitivity, Superconducting Quantum Interference Device (SQUID), Feasibility, Nonacoustic, Ocean Transparency, Electromagnetic Waves, Wavelength Dependence

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
unclassified	unclassified	unclassified	unlimited	13	

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I. INTRODUCTION

For many years the desire of the antisubmarine warfare community has been to render the oceans transparent. To explore the prospects of developing a sensor that can "see" through sea water by use of electromagnetic radiation, consider first the attenuation of such radiation in sea water as a function of frequency as shown in figure 1, which was taken from reference (a). It is seen that in only two portions of the spectrum is the attenuation less than 1 decibel per meter: in the visible part of the spectrum and at frequencies less than 1 kilohertz. Exploitation of the visible part of the spectrum is being pursued in the development of LIDAR (light detection and ranging) systems employing blue-green lasers. The purpose of this technical

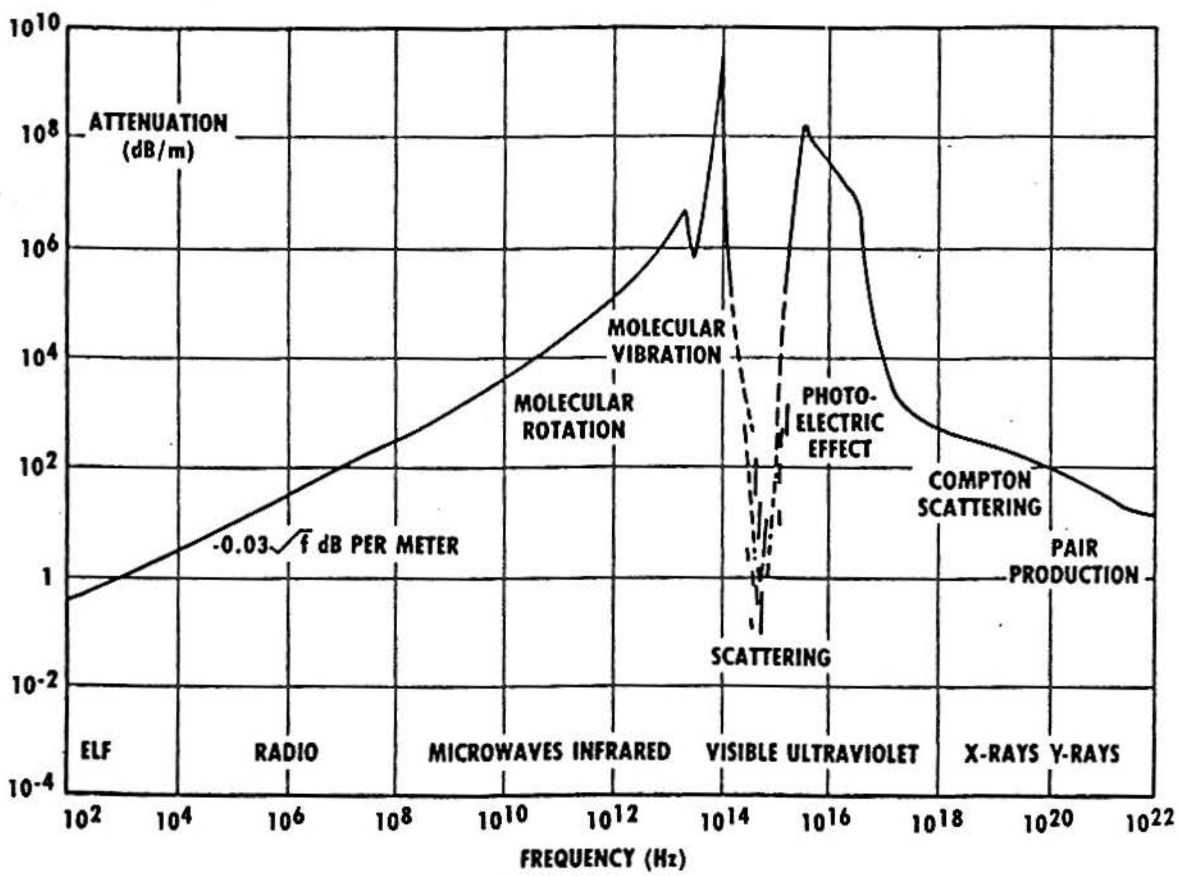

Fig. 1. Attenuation of electromagnetic energy in sea water

note is to explore the feasibility of developing a practical radar capable of operating at extremely low frequencies and of detecting and localizing, at militarily useful ranges, submarines at reasonable operating depths.

II. BACKGROUND

The ELF radar concept is illustrated in figure 2. A bistatic system is envisaged, with the source and receiver widely separated, to reduce the likelihood of saturation of the receiver by direct emanations from the source. (Because the reciprocal of the frequency of the radiation would be large in comparison with the time required for the radiation to travel from the source to the target and to the receiver, it appears that a pulsed, range-gated system would not be feasible.) Radiation would emanate from the (dipole) source, suffer inverse cube law spreading loss in passing

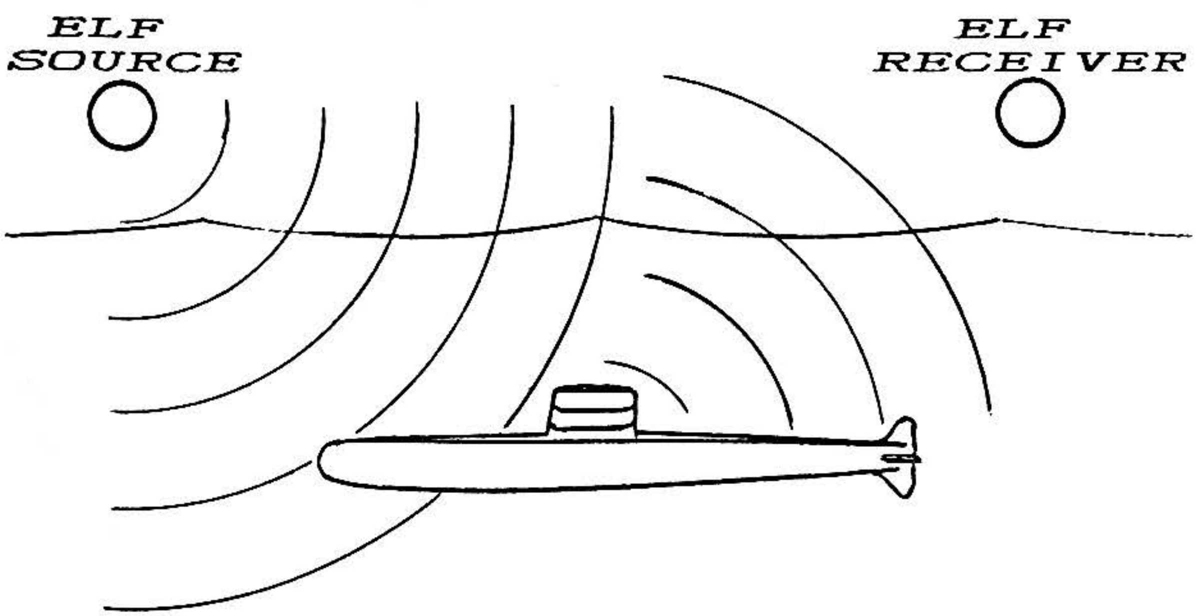

Fig. 2. ELF radar concept

Note. This illustration does not show the great reduction in wavelength of the electromagnetic radiation as it enters the water nor the change in its direction of propagation to nearly normal to the surface.

through the atmosphere (because at such wavelengths the target would be in the near field), and strike the surface of the water. At the air-water interface, because of a tremendous reduction in the speed of propagation, the major portion of the wave energy would be reflected upward and the small portion that penetrates the water would propagate nearly vertically downward. If there is a submarine present whose electrical conductivity and/or magnetic permeability differ(s) significantly from that of the sea water in which it is immersed, a small portion of the incident energy would be scattered in an upward direction and, in principle, detected by the receiver.

In reference (b), two types of sources are considered: (1) a large-area coil of copper wire wrapped around an aircraft (wingtip to tail to wingtip to nose to wingtip) through which a large alternating current is passed, and (2) a rotating superconducting electromagnet, which might be mounted on a ship or on an aircraft. These two approaches are discussed in subsequent sections.

III. FACTORS INFLUENCING CHOICE OF FREQUENCY

As shown in figure 1, for frequencies less than 100 MHz, the attenuation of electromagnetic radiation in sea water varies as the square root of frequency. (A value of 3 mho/meter was assumed for the conductivity of sea water in the preparation of figure 1.) Accordingly, if attenuation were the only consideration, the best performance would be obtained at the lowest possible frequencies. However, to obtain significant scattering of the electromagnetic waves by a submarine, the wavelength (in sea water) of the electromagnetic waves should be considerably smaller than the dimensions of the submarine hull. If one considers that the wavelength of 1-kHz electromagnetic waves is 186 statute

miles, one might be inclined to despair. However, as is shown later, the speed of propagation of ELF electromagnetic radiation in sea water is many orders of magnitude less than in air and there is a concomitant reduction in wavelength. Another factor that strongly influences the choice of frequency is that the difficulty of generating ELF radiation varies as the method of generation which, in turn, is dependent upon the frequency desired.

IV. ELECTROMAGNETIC WAVES IN SEA WATER

Consider the propagation of plane ELF waves of frequency f in sea water of conductivity 4 siemens/meter (4 mho/meter). The speed of propagation v is given by

$$v = 1600\ f^{\frac{1}{2}}\ \text{meter/second.} \qquad (1)$$

A striking consequence of equation (1) is that at frequencies of the order of 1 hertz, electromagnetic waves propagate in sea water at about the same speed as sound waves. The wavelength λ of the ELF waves is

$$\lambda = 1600/f^{\frac{1}{2}}\ \text{meter} \qquad (2)$$

and the attenuation coefficient k is

$$k = 0.004\ f^{\frac{1}{2}}\ \text{meter}^{-1}. \qquad (3)$$

V. CONFLICTING DESIDERATA

To try to satisfy the requirement that the undersea wavelength of the ELF radiation be small in comparison with the dimensions of a submarine, one may assume a wavelength

equal to one-fourth of a submarine length or approximately 125/4 meters. Equation (2) then yields a frequency f = 2.6 kHz but equation (3) yields an unacceptably large attenuation coefficient k = 0.20 $meter^{-1}$. On the other hand, if one can tolerate a transmission loss from attenuation in sea water of as much as 99% on a one-way trip to a submarine at a depth of 300 meters, a frequency of less than 15 Hz would be required. (In the foregoing, spreading loss was ignored.) The corresponding wavelength, from equation (2), would be λ = 413 meters or about 3.3 submarine lengths. Scattering of radiation of this wavelength would be small.

In summary, there are conflicting requirements: to achieve significant penetration, a frequency of **less** than about **100 Hz** is required; to achieve significant scattering from the submarine, a frequency of **more** than **1000 Hz** is required.

VI. LARGE COIL CARRYING AN ALTERNATING CURRENT

For an air-core coil of area A consisting of N closely spaced turns of wire carrying a current i, the magnetic moment is

$$\mu = N\ i\ A \quad \text{ampere turns.} \tag{4}$$

The magnitude of the magnetic induction B at a distance z along the axis of the coil is

$$B = (\mu_0/2\ \pi)(\mu/z^3) \quad \text{tesla} \tag{5}$$

in which μ_0 is the magnetic permeability constant of free space having a value of $4\ \pi \times 10^{-7}$ weber per ampere meter.

To get some idea of the magnitudes involved, suppose one wished to produce a magnetic field equal to that of the earth (B_E = 0.5 gauss = 0.5 x 10^{-4} tesla) at a range of 100 meters from the coil. The large magnetic moment μ that the coil would have to develop to produce even this rather weak field at a distance that would be relatively short for ASW purposes would be

$$\mu = 2 \pi B z^3 / \mu_0 = 2.5 \times 10^8 \ \mathrm{A \cdot m^2}. \qquad (6)$$

Next consider an aircraft such as a P-3, having a wing span of 30.4 meters and a length of 35.6 meters, at whose extremities a large kite-shaped, vertical-axis, air-core coil is attached. The length of each turn of wire would be 87.2 meters and the coil area would be 364 meter^2. To produce a magnetic moment of only 10^6 A·m^2, (i.e., 0.4% of the above value) would require a current loop of 2747 ampere turns. This could be achieved by passing a current of 325 amperes through an 8.45-turn coil of AWG 0000 copper wire wrapped around the aircraft as described above. The resistance of the wire would be 0.133 ohm at an assumed temperature of 50°C. The power dissipated would be 14 kW and the weight of the copper would be 705 kg. Yet, even with such a heroic effort, the magnetic field produced would drop off to a value of the earth's field (0.5 gauss) at a distance of only 17.8 meters.

VII. ROTATING SUPERCONDUCTING ELECTROMAGNET

Consider next the possibility of using a superconducting electromagnet as the source. Because the electrical resistance R of a superconducting coil would be immeasureably small, the inductive time constant t_L = L/R would be enormous; as a consequence it would be impossible to use a time-varying current (even at ELF) to produce the

desired radiation field. An alternative is to rotate the coil while maintaining a steady current in it.

Reference (c) provides a procedure for estimating the weight and diameter of a superconducting electromagnet as a function of its magnetic moment. Table 1 gives three such examples.

Magnetic Moment ($A \cdot m^2$)	Weight (lb)	Diameter (m)
10^6	400	6
10^8	800	5
10^8	1500	4

Table 1. Sizes and weights of superconducting electromagnets

It is interesting to note that, for a given magnetic moment, the weight **increases** as the diameter **decreases**. This occurs because the magnetic stresses are greater in the more compact magnets and therefore greater structural strength is required.

Installation of a superconducting electromagnet in an aircraft is not without precedent. In 1972 a **nonrotating** superconducting electromagnet having a magnetic moment $\mu = 10^6$ $A \cdot m^2$ was flight tested in a CH-53 helicopter to investigate its utility for Navy mine sweeping. Reference (d) describes the effects of the magnet on the helicopter's flight system, particularly, the instruments.

VIII. CALCULATED SIGNAL STRENGTHS

Reference (e) provides calculated signal strengths for a number of situations. One representative example is the following. Assume a source of magnetic moment $\mu = 10^6$ A·m^2 at a height of 100 meters above the surface and a submarine at a depth of 100 meters at a distance of 1000 meters. For purposes of calculation, the receiver is assumed to be collocated with the source. The signal strength at the receiver from the submarine was calculated to be $B_S = 10^{-15}$ tesla.

IX. RECEIVER SENSITIVITY

It is assumed that a state-of-the-art superconducting quantum interference device (SQUID) having a sensitivity of 10^{-12} T/Hz$^{\frac{1}{2}}$ (tesla per root hertz) would be used as the front end of the receiver. If an integration time of 30 seconds is assumed, a signal of magnetic induction $B = 9 \times 10^{-13}$ T would provide a signal-to-noise ratio of 5. Here it is assumed that the only noise in the system is that of the SQUID itself.

X. ASSESSMENT

If one compares the expected signal strength for the example given (10^{-15} T) with the above optimistic estimate of receiver sensitivity (9×10^{-13} T), one concludes that, at best, one is at least two orders of magnitude short of the required sensitivity. This analysis does not take into account other noise sources or interfering effects, such as the magnetic fields associated with eddy currents generated in the sea water by the time-varying magnetic field from the source. Additionally, the problem of detecting an extremely

feeble signal from the target against a background of direct radiation from the source is not insignificant.

XI. ADDITIONAL COMMENTS

In the past year claims have been made that an ELF radar (or active magnetic anomaly detector) similar to that discussed herein could be built that would yield detection ranges against submerged submarines out to twenty miles. In the process of calculating the background of direct radiation from the source against which the target signal would have to be detected, it became apparent that one would have difficulty in detecting at 20 nmi radiation **directly** from a source having a magnetic moment as intense as 10^8 $A \cdot m^2$, let alone the small portion that penetrates the air-water interface, passes through the water, is scattered weakly from the submarine, and re-emerges into the atmosphere. Table 2 gives calculated values of direct path signal strengths as a function of source magnetic moment and range in air. Loss from only inverse cube law spreading was considered.

MAGNETIC INDUCTION (tesla)			
Magnetic Moment ($A \cdot m^2$) / Range (m)	10^6	10^8	10^{10}
1,000	2.0×10^{-10}	2.0×10^{-8}	2.0×10^{-6}
10,000	2.0×10^{-13}	2.0×10^{-11}	2.0×10^{-9}
20,000	2.5×10^{-14}	2.5×10^{-12}	2.5×10^{-10}
37,000 (20 nmi)	3.9×10^{-15}	3.9×10^{-13}	3.9×10^{-11}

Table 2. Direct path source signal strength

XII. CONCLUSION

Development of a practical ELF radar for the detection of completely submerged submarines at normal operational depths in sea water does not appear feasible.

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